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THE SPATIAL RIGIDITY OF TECHNOLOGICAL ROBOTS
ПРОСТОРОВА ЖОРСТКІСТЬ ТЕХНОЛОГІЧНИХ РОБОТІВ

В статье рассмотрена актуальная проблема определения пространственной статической жесткости «однодуговых» и «двуруких» технологических промышленных роботов. Разработана методика расчета и построения поверхности пространственной жесткости промышленного робота с целью дальнейшего использования для определения точности механической обработки деталей путем резания. Установлено, что подход к определению пространственной жесткости обрабатывающих машин является общим для роботов и станков.

Ключевые слова: *промышленные роботы, пространственная жесткость, статическая жесткость*

Розглянуто актуальну проблему визначення просторової статичної жорсткості технологічних промислових роботів "одношарова" та "дворучна". Розроблено метод обчислення та конструювання поверхні просторової жорсткості виробничого робочого робота з метою подальшого використання для визначення точності механічної обробки деталей за допомогою різання. Встановлено, що підхід до визначення просторової жорсткості обробних верстатів є загальним для обох роботів та верстатів.

Ключові слова: *промислові роботи, просторова жорсткість, статична жорсткість*

The article considers the actual problem of determining the spatial static rigidity of "one-arc" and "two-handed" technological industrial robots is considered. The method of calculating and constructing the surface of the spatial rigidity of a manufacturing industrial robot with the purpose of further use for determining the accuracy of machining of parts by cutting is developed. It is established that the approach to determining the spatial rigidity of machining machines is common for both robots and machine tools.

Keywords: *industrial robots, spatial stiffness, static rigidity*

In the automated productions are widely used technological industrial robots (IR), which perform transport, welding, painting and other operations (Figure 1). Along with CNC machines, technological machining IRs are widely used for processing objects of cutting production (Figure 1d). At the same time, processing IR is used for milling, drilling, boring and other mechanical precision machining operations.

a) b) c) d)

Figure 1. Industrial robots of various technological purposes
a) transport; b) welding; c) painting; d) processing

The overwhelming majority of the IRs are "one-handed" robots that have simple, traditional chain-type arrangements with a number of "knees" three or more (Figure 2a,b). A more complex arrangement has "two-handed" IR (Figure 2c). Robots which are based on mechanisms with parallel kinematics of "hexapod" type (Figure 2d) are produced as well and others.

It is designed that at the end element of the IR the special flange is provided and a working element is attached to it. The examples of the working elements are special grab, a welding head or a paint sprayer, and on the machining IR - spindle assembly (Figure 3).

Machining IRs are used in those mechanical operations, where they are able to provide the required precision machining. The accuracy of processing depends on the properties of the robots elastic system (ES), in particular on the characteristics of rigidity in the cutting zone. The main problem of the use of machining robots is the uncertainty of the rigidity of an elastic system, which varies in space, depending on the direction of the force of cutting.

a) b) c) d)

Figure 2. Compositions of industrial robots
a) with 3 "knees"; b) with 8 "knees"; c) "two-handed"; г) "hexapod"

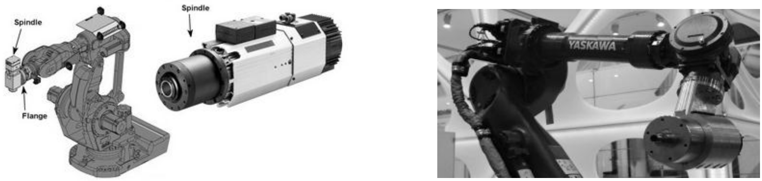


Figure 3. Usage of a special flange for attaching the working body of the IR (in these cases – the spindle node)

The purpose of the work is an analytical definition for building the surfaces of the spatial rigidity of "one-arc" and "two-handed" machining industrial robots.

Consider the design of "one-armed" machining robot (Figure 4).

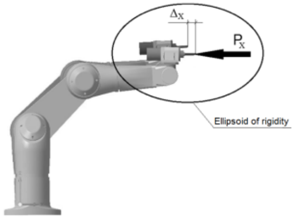


Figure 4. "One- handed " IR with an ellipsoid of rigidity

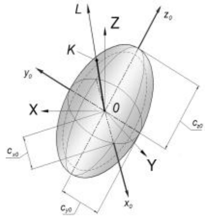


Figure 5. Typical ellipsoid of rigidity

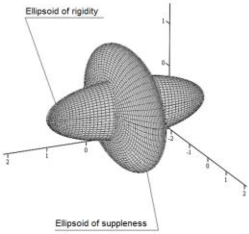


Figure 6. Hedged ellipsoids of rigidity and suppleness

The static rigidity of the IR along the X axis is defined as $C_X = P_X / \Delta_X$. Along other axes - are similar. The spatial rigidity of a technological processing machine (machine or robot) is represented in the form of ellipsoids of rigidity with the center in the cutting zone (point O) that are shown in [1,2]. Ellipsoid rigidity is constructed on the main rigidity of the ES and is mathematically described by a matrix of rigidity in the form

$$C = diag[C_{x0}, C_{y0}, C_{z0}, C_{\varphi x0}, C_{\varphi y0}, C_{\varphi z0}], \tag{1}$$

which consists of elements of translational rigidity along the corresponding axes C_{x0}, C_{y0}, C_{z0}, and a rotary rigidity around the same axes $C_{\varphi x0}, C_{\varphi y0}, C_{\varphi z0}$. In the general case, the directions of the main axes of rigidity do not coincide with the directions of the coordinates of the system axes.

In the cutting zone, the accuracy of the processing is practically influenced only by the translational spatial rigidity, which is geometrically realized by the surface of the ellipsoid constructed with the center at the point O in the three-dimensional coordinate system (Figure 5). In a tensor number, an ellipsoid of translational rigidity is described by a quadratic form (quadric) and a second order tensor (analogous to the inertial tensor).

$$C^{\Pi} = \begin{bmatrix} C_{x0} & 0 & 0 \\ 0 & C_{y0} & 0 \\ 0 & 0 & C_{z0} \end{bmatrix} \tag{2}$$

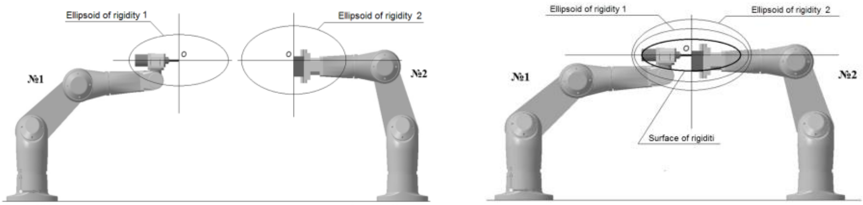
Sometimes it is more convenient to use an ellipsoid of suppleness, which is reciprocal (conjugated) to the ellipsoid of rigidity and is constructed similarly (Figure 6). With known cutting forces P with the help of robots ES ellipsoids, can determine the deformation values in the cutting zone in any direction of the working space.

Two robots can be used to process parts (Figure 7a): one cutting tool (with a rigidity ellipsoid C1), and the other - a fixing part in the working space (with a rigidity ellipsoid C2).

During cutting, the centers of both ellipsoids coincide in one point O (the center of the cutting zone). In this case, the resulting rigidity of the system will be reduced and described not by the ellipsoid, but by the resulting surface of rigidity. This surface can be constructed graphically based on the matrix expression

$$C = [C_1 + C_2]^{-1} \cdot C_1 \cdot C_2 \tag{3}$$

During processing, various cutting tool arrangement locations are possible with respect to the workpiece, as it is shown in the part in Figure 8. In this case, unlike the location of the axes in Figure 7, the ellipsoid axes will no longer be collinear and the shape of the surface of the spatial rigidity will be even more distinct from the ellipsoid.



a) b)

Figure 7. Application of two industrial robots with two ellipsoids of rigidity (C1 and C2)
a) in a non-working condition; b) during cutting

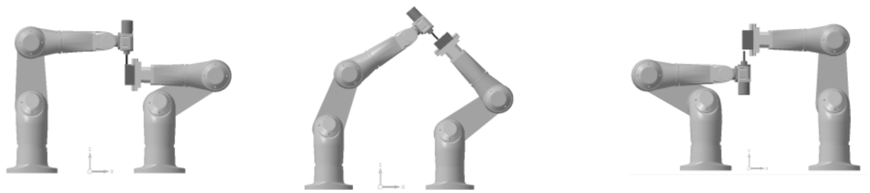


Figure 8. Variants of technological schemes of processing by two robots

In this case, the matrix expression (3) will be changed taking into account the matrices M1 and M2 of the rotation of the ellipsoids relative to the principal coordinate axes of the system, respectively

$$C = [C_1M_1 + C_2M_2]^{-1} \cdot C_1M_1 \cdot C_2M_2 \tag{4}$$

In industry, the aforementioned version of the usage of two robots was transformed into the creation of "two-handed" robots, depicted in Figure 9.

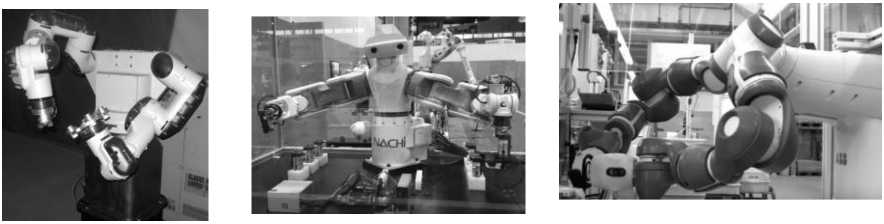


Figure 9. Options for the layout of two-handed industrial robots

Thus, the layout of "two-handed" machining robots is actually reduced to the layout of the machine tools, in which the subsystems of the tool and the parts interacting through the cutting process are attached to the base subsystem (frame). That is, in the IR can be used methods of study of spatial rigidity, which are used for the study of machines, for example, from work [3].

Conclusions

As the results of research that were carried out, the general approach to the definition of spatial static rigidity of machining robots practically do not differ from the similar approach to the definition of spatial rigidity of machine tools.

The developed approach to the determination of the spatial static rigidity of the processing technological robots should be used when using "one-armed" and "two-handed" industrial robots. This allows the design stage to determine the surface of the static spatial rigidity of the design of the industrial robot, and allows in the future to choose the rational modes of processing and to predict the accuracy of the machined parts.

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